



Coal–biomass co-combustion: An overview

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ABSTRACT

The energy sector in the global scenario faces a major challenge of providing energy at an affordable cost and simultaneously protecting the environment. The energy mix globally is primarily dominated by fossil fuels, coal being the major contributor. Increasing concerns on the adverse effect of the emissions arising from coal conversion technologies on the environment and the gradual depletion of the fossil fuel reserves had led to global initiatives on using renewables and other opportunity resources to meet the future energy demands in a sustainable manner. Use of coal with biomass as a supplementary fuel in the combustion or gasification based processes is a viable technological option for reducing the harmful emissions. Co-combustion of coal with biomass for electricity generation is gradually gaining ground in spite of the fact that their combustion behavior differ widely due to wide variations in their physical and chemical properties. This article deals with the technical aspects of co-combustion with emphasis on the fundamentals of devolatilization, ignition, burnout and ash deposition behavior along with the constraints and uncertainties associated with the use of different types of biomass of diverse characteristics and the likely impact of partial replacement of coal by biomass on the emission of CO₂, SO_x, NO_x. Other issues of no less importance like sustained availability of biomass, transportation and storage, effect on biodiversity, etc., are left out in the study. The investigations reported in the study reflect the potential of biomass as co-fuel, and the scope of maximizing its proportion in the blend in the coal based power plants and the derived benefits.

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1. Introduction

Co-combustion is one of the most advantageous ways of utilizing biomass and waste for replacement of fossil fuels for

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stationary energy conversion. Much difficulties are being faced for retrofitting coal-fired boilers designed for pulverized coal combustion to operate in co-combustion mode. In Indian context the nature and gravity of such challenges are under explored. In India varieties of biomass products are available which do have tremendous potentiality for co-combustion with pulverized coal. Based on the emerging need, detailed investigations are felt necessary to examine the compatibility of different kinds of biomass with coal and to select suitable blend composition(s) before utilizing those biomass products in utility operation as co-fuels [1–4].

Power generations from coal/biomass blends are increasingly gaining importance as the biomass is a renewable energy source and is considered to be carbon neutral. Co-firing and co-gasification of fossil fuels and biomass (sawdust, rice husk, coconut coir, straw, corn cob, bagasse etc.) are presently being considered to have enhanced importance because partial replacement of precious fossil fuel is possible in such cases, which give extensive support to the growth of power sector in developing countries like India. Biomass co-combustion also represents a low cost, sustainable, and renewable energy option that ensures reduction in net CO₂, SO_x and often NO_x emissions and also in the anaerobic release of CH₄, NH₃, H₂S, amides, volatile organic acids, mercaptants, esters, and other chemicals [1–7] resulting in several benefits. The advantages of this technique as described above have been highlighted by several researchers [8–15].

Compared to dedicated biomass or waste fired plants, the addition of biomass or waste to high efficiency coal-fired power plants can greatly increase the efficiency of utilizing these fuels [11]. Besides, the cost of retrofitting an existing coal-fired power plant to a co-combustion plant can be considerably lower than building a new dedicated biomass or waste-fired plant [16]. Furthermore, to minimize the fluctuating supply of some secondary fuels (such as straw) and to secure the power generation, co-combustion can be operated in a flexible mode (i.e. with different shares of secondary fuels) [12].

Actually strictures in respect of GHG emission and scenario of fossil fuel depletion strengthened the foundation of the rationality for co-combustion. Biomass fuels have sometimes been reported to have peculiar combustion features particularly when they are subjected to thermal shock [17]. Biomass fuels having much volatile

matter content, may find their possible utilization in co-firing with low volatile coals. Biomass fuels contain higher volatile matter with higher oxygen content and as such possibility of easy release of volatile matter in a combustor is more as compared to coal. All these characteristics of biomass have been found to have large influence on the burnout time of blends of coal and biomass [3,17–19].

1.1. Background

Increasing concerns about the environmental impacts of power generation from precious fossil fuels have promoted the development of more sustainable means of generating power. These have included increasing the fraction of renewable and sustainable energy in the national energy supply.

The co-firing of biomass with coal in conventional coal-fired boilers can provide a reasonably attractive option for utilization of biomass for power generation. Co-firing can use the infrastructure which is associated with the existing fossil fuel based power systems and requires some capital investment. In most of the countries co-firing is one of the most economic technologies available for providing significant reduction of CO₂.

1.2. Comparison of cost and emission

The net electrical efficiency of a co-fired coal/biomass power plant ranges from 36% to 44%, depending on plant technology, size, quality and share of biomass. While a 20% co-firing (as energy basis) is currently feasible and more than 50% is technically achievable, the usual biomass share today is below 5% and rarely exceeds 10% on a continuous basis. A high biomass share implies lower GHG emissions. It is estimated that 10% biomass co-firing in coal power plants could reduce CO₂ emissions from 45 million to 450 million ton/year by 2035, if no biomass upstream emissions are included. However, high biomass shares involve several technical issues including sustained availability of biomass and likely slagging, fouling and corrosion problems. The overall cost of co-firing is sensitive to the plant location and the key cost element is the biomass feedstock. The investment cost for retrofitting a coal-fired power plant for co-firing is in the range of USD 430–500/kW for

Table 1
Primary energy consumption by energy sources and region in 2006, PJ/year [22].

	Modern biomass	Traditional biomass	Other renewables	Conventional energy	Total primary energy	Modern biomass as % of primary energy
World	16,611	33,432	13,776	409,479	473,319	3.5
OECD	8442	42	6783	222,369	237,636	3.6
OECD North America	4158	–	3276	112,959	120,393	3.5
US and Canada	3801	–	2898	106,281	112,980	3.4
Mexico	357	–	399	6678	7392	4.8
OECD Pacific	882	42	798	36,561	38,283	2.4
OECD Asia	504	42	525	31,374	32,445	1.6
OECD Oceania	378	–	252	5208	5838	6.5
OECD Europe	3402	–	2688	72,828	78,939	4.3
OECD Europe–EU	3129	–	1785	69,384	74,298	4.2
Transition economics	693	–	1176	44,688	46,536	1.5
Russia	273	–	672	26,901	27,867	1.0
Developing countries	7434	33,432	5817	1362,69	182,994	4.1
China	315	8988	1323	49,602	60,144	0.5
East Asia	1092	3633	1197	20,202	26,145	4.2
Indonesia	126	1680	357	5418	7560	1.7
South Asia	1302	9828	504	18,627	30,261	4.3
India	1092	8043	357	15,582	25,074	4.4
Latin America	2394	1239	2373	15,834	21,840	11.0
Brazil	1680	357	1176	5502	8736	19.2
Middle East	21	63	105	19,341	19,551	0.1
Africa	2310	9702	315	12,726	25,074	9.2

co-feed plants, USD 760–900/kW for separate feed plants and USD 3000–4000/kW for indirect co-firing. These costs are still significantly lower than the cost of dedicated 100% biomass power plants. The biomass fuel costs depend on the biomass type, volume traded and geographic location. The costs for globally traded biomass pellets are around €12/MWh higher than the costs of coal. Advanced pelletization and – in the near future torrefaction – can increase the energy density of biomass, reduce transportation costs and improve storage performance. Taking into account all cost components and assuming a discount rate of 7%, a typical leveled electricity cost for biomass co-firing ranges from USD 22–130/MWh, with the actual cost depending on assumptions about location, biomass type, co-firing technology and plant capacity factors [20].

Biomass is considered as an environment friendly fuel and has some advantages over fossil fuels like coal. Biomass contains little sulfur and nitrogen. Biomass co-combustion has vital positive SO₂ reductions of up to 75%. Most of nitrogen in biomass is converted to NH₃ products such as ammonia NH₃ during combustion. Growing plants for use as biomass fuels may also help keep CO₂ levels balanced. Plants remove CO₂ as one of the greenhouse gases from the atmosphere when they grow. Moreover, thermal utilization of biomass can contribute to the reduction of CO₂ emissions since the same amount of CO₂ is extracted from air during the balance [21].

An evaluation of the CO₂ growth period of the plants as it is released by combustion CO₂ balance shows that, compared with the combustion of hard coal, the CO₂ emissions can be reduced by approximately 93%. The alkaline ash produced from biomass also captures some of SO₂ and CO₂ produced during combustion. Co-firing of biomass residues mitigates greenhouse gases by avoiding CH₄ release from the landfilled biomass. It is believed that CH₄ is 21 times more potent than CO₂ in terms of global warming impact. Co-firing also reduces NO₂ emission as great as 15% [21].

1.3. Status of bio-energy

Table 1 indicates the share of bio-energy in various regions in the world is still very limited. In industrialized countries the contribution of biomass is estimated is about 4%. In developing countries, around 22% of energy used originated from biomass, but the majority of it is used non-commercially in traditional applications.

2. OECD: organization for economic co-operation and development

The use of biomass is widespread, as shown in Fig. 1. There are a total of 62 countries in the world currently producing electricity

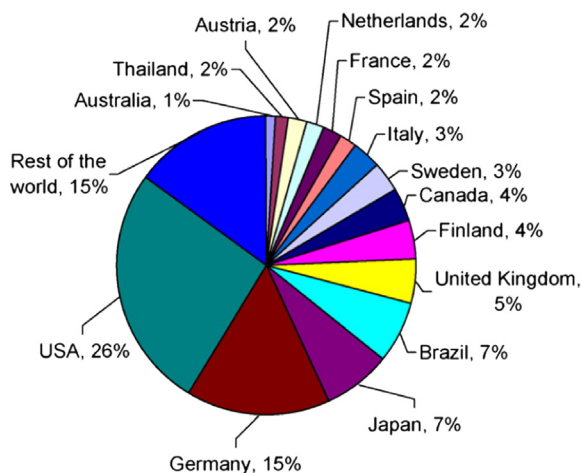


Fig. 1. Global distribution of biomass energy use in 2008.

from biomass. USA is the dominant biomass electricity producer at 26% of world production, followed by Germany (15%), Brazil and Japan (both 7%) [23].

Up to 2010 more than 150 coal-fired power plants have experienced some co-firing activity (most in USA: 40, Sweden: 15, Germany: 27, and Finland: 14). In Asia pacific: Australia, China, Indonesia, Malaysia, Taiwan, and Thailand; Europe: Austria, Belgium, Denmark, Finland, Germany, Italy, Netherlands, Norway, Poland, Romania, Spain, Sweden, and UK; North America: Canada and USA; and South Africa are also benefiting from the co-firing [24].

Drax a UK based power producing company is undertaking the largest biomass co-firing project in the world, in which renewable biomass is burnt alongside coal to produce electricity. This is the cleanest and most efficient coal-fired power station (4000 MW) in the UK, meeting 7% of the country's power needs [24].

Most of the developed and developing countries are considering co-firing as an attractive option by providing incentives. US Government allows co-firing by providing Renewable Standard Portfolio and Greenhouse gas trading in some regions (e.g., RGGI). UK Government regulators are encouraging co-firing by allowing Renewable Obligation Certificates (REC) [24].

The present installed (conventional fuel) generating capacity in India is 223,343.60 MW (as on 31.03.2013). The share of hydro with 39,491.40 MW capacity is about 17.7%. Thermal accounts for maximum share of 67.8% with 151,530.49 MW. It comprises of 130,220.89 MW from coal, 20,109.85 MW from gas and 1199.75 MW from oil. The share of Nuclear power is about 2.1% with 4780 MW. The share of Renewable Energy Sources (RES) which includes Small Hydro Projects, Biomass Gasifier, Biomass Power, Urban and Industrial Waste Power is about 27,541.71 MW i.e. 12.3% [25]. A replacement of certain percentage of coal with biomass can definitely solve India's energy security creating substantial rural income (Rs. 15,000 crs/year as mentioned by MNRE) and thereby reducing the imports [24].

This paper deals basically with fundamentals of coal combustion and co-combustion which includes devolatilization behavior, ignition behavior, flame stability, char reactivity, burnout behavior, environmental aspects, ash deposition behavior, burning performances of coal–biomass blends and brief review of work carried out by different groups of researchers in the area of co-combustion. Generation of information to provide case-specific/region specific logistics in favor of co-combustion particularly in Indian context is the heart of those studies. Moreover, case specific detailed analysis of the process may be the driving force to boost up the implementation exercise by the power producers in India. The work explored the utilization possibility of raw biomass and low temperature biomass char. For this purpose biomass and char samples were ground to identical fineness level and blended with reference coal samples. Behavioral pattern of different blends were noticed and advantageous effects and limitations were identified. Attempts were also taken to identify maximum allowable biomass content for a particular combination in our work [26–29].

2.1. Fundamentals of coal combustion and co-combustion

In order to comprehend the coal biomass co-combustion, the basics of coal combustion and co-combustion should be understood thoroughly.

2.1.1. Devolatilization behavior

Organic structure present in the solid fuel can experience thermal decomposition and release volatile matter when it undergoes a high temperature environment. This phenomenon is known as devolatilization. The devolatilization products are mainly CO₂, CO, H₂O, H₂, CH₄ and other light hydrocarbons, tar, soot and char.

Devolatilization behavior, such as decomposition temperature, rate and product distributions, can subsequently influence the ignition, burnout and pollutant formation during combustion [30,31].

The devolatilization characteristics of coal has been investigated by experiments and modeling, with a number of reviews available [30,32]. In coal the main organic structures present can be categorized as aromatic groups, aliphatic group and side chains [33]. In general lower rank coals produce much light gases during the primary devolatilization, as less amount of aromatic carbon and more amounts of aliphatic groups are present in lower rank coals. For the devolatilization of intermediate rank coals tar formation is generally most significant [34,35], as these coals contain more aliphatic groups than the high rank coals and more aromatic carbon than the low rank coals, which favor tar formation. It was reported that during the primary devolatilization, by increasing the pyrolysis temperature formation of CO, CO₂, CH₄ and tar is promoted, whereas this effect may be insignificant when temperature is above 800 °C [36]. At elevated pressure, the formation of tar as well as the total volatile species can be inhibited to some extent when the primary devolatilization is carried out [31]. After the release of tar and light gases from the primary devolatilization of coal, they may undergo secondary reactions and produce soot and different light gases [37]. The thermal cracking and soot formation are involved with secondary reactions of tar. In the thermal cracking, the side chains and functional groups in the tar are cracked to the formation of light gases [38].

Several researchers worked in the area of devolatilization of biomass and waste [39]. The major organic components present in biomass and biomass originated waste are usually cellulose, hemicellulose and lignin [39,40]. During the devolatilization process, the hemicellulose often decomposes at lower temperature and released more volatiles, less tar and less char. Lignin can produce more char during devolatilization than that of cellulose or hemicellulose due to amorphous cross-linked resin [40]. The devolatilization behavior of coal and biomass is different due to the structural differences. The devolatilization of the biomass occurs at lower temperature than that of coal, and produces more light gases and tar. The devolatilization of biomass is influenced by the biomass properties, temperature and heating rate. A higher temperature usually decreases the char yield and increases the light gas formation. At intermediate temperature range (~500 to 700 °C), maximum yield of tar is frequently observed, which is related to both the primary release and secondary reactions of tar [41].

The mutual interactions between coal and biomass during devolatilization have been studied through a thermogravimetric analyzer, a fixed bed and an entrained flow reactor. A number of investigations reflected that the interactions between coal and biomass are negligible during the devolatilization. All these studies suggested that the devolatilization behavior of the fuel blends is additive.

The volatiles are released from biomass may react with coal or coal volatiles when coal is pyrolyzed together with biomass. These reactions may favor the formation of volatiles from the fuel blends, and inhibit the char yield [41–47]. The probable cause is that, the devolatilization of biomass may produce huge amount of hydrogen, which can prevent the recombination and cross-linking reactions of free radicals, and so suppressing the char formation [41]. Jones et al. investigated the devolatilization behavior during co-pyrolysis of pine wood together with one of three coals of a different rank, lignite or high-volatile bituminous of a different origin [45]. They found that in the batch pyrolysis tests, synergy (non-additive behavior) was observed and the blend pyrolysis oil contained a decrease in aromatics and an increase in phenols than would be expected for additive behavior. The molecular weight distributions of the evolved tars also show non-additive behavior. In the TGA experiments, additive behavior was observed for all the

coal–pine wood blends. Biagini et al. [48] also studied devolatilization behavior of different coals and biomasses under heating conditions typical of conventional pyrolysis processes. They found that in the operative conditions used (i.e. at heating rate 20 °C/min and at high nitrogen flow rate), primary reactions of the thermal decomposition of biomass fuels are not significantly affected by the presence of coal, and also coal does not seem to be influenced by the release of volatile matter from biomass. This led to the first conclusion that the weight loss of a blend can be obtained from the weighted sum of reference materials. Katanaki et al. [49] on the other hand investigated behavior of Greek pre-dried lignite, four biomass materials and their blends in the devolatilization stage by thermogravimetry. They found that the biomass materials have higher thermochemical reactivity than lignite and shorter devolatilization times that can ensure their complete conversion within operating lignite-fired boilers. Devolatilization of biomass occurs at much lower temperature than that of coal and produces much more tar and light gases. Both additive and non-additive behaviors were observed during devolatilization of coal–biomass blends. Ignition behavior and flame stability is another aspect of co-combustion.

2.1.2. Ignition behavior and flame stability

Ignition and flame stability are very much significant for carbon burnout and formation of pollutants such as NO_x during solid fuel combustion. The ignition behavior of solid fuel particles may follow two mechanisms, one is homogeneous ignition and the other is heterogeneous ignition. Ignition of the volatiles released from the fuel particles is homogeneous ignition and heterogeneous ignition generally results from the direct attack of oxygen on the fuel/char particle surface. The ignition behavior of solid fuels is influenced by several factors such as fuel properties, particle size, temperature, heating rate, gas compositions, particle number density, fluid flow etc. [50,51].

In the co-combustion of pulverized coal and biomass, the biomass particles are generally larger than the coal particles [10,52]. Biomass is more difficult and expensive to grind than coals [10,16], and the chemical characteristics of biomass allow it to have a relatively large particle size in co-combustion. The ignition performance of biomass and coal may be relatively different, due to the differences in particle size and fuel properties, which can influence the flame characteristics in co-combustion. Experiments have been carried out in a reactor for comparing the ignition/flame characteristics of pulverized coal and sawdust [53]. Compared to the coal flame, a more intense and wide flame was observed near the burner zone during the sawdust combustion, which may be attributed to the volatiles released from the fine fraction of sawdust particles. Alternatively, a second flame stage appears downstream of the near-burner region during sawdust combustion, which is most probably for the combustion of the large sawdust particles [53].

Influences of co-firing of coal and different biomass on the flame temperature, flame stability were investigated by using vision based measurement techniques on a combustion test facility [54]. The temperature of the co-firing flame was detected to be slightly greater than that of coal flame, which is resulted from faster heat release caused by the volatiles from biomass [54]. Similar increased flame temperature was observed in case of coal/sawdust co-combustion in an electrically heated drop tube reactor [55].

The relatively large size of biomass particles, along with high moisture content, may result in a delayed ignition or devolatilization [54]. Besides, biomass generally contains relatively large volatile content and starts to decompose at lower temperatures, which is a favorable condition for generating a more intensive flame than coal flame. Chi et al. [56] investigated the ignition

behaviors of pulverized coals and coal blends in a drop tube furnace using a flame monitoring system and observations in respect of ignition behavior were reported to be quite similar to coal–biomass co-combustion as described above. In case of coal-blends also, ignition property was found to be controlled by the component coal having higher volatile matter and its proportion in the blend. These are also related to burnout behavior. Wide flame and increased flame temperature were observed with respect to coal combustion during co-combustion. As char combustion is the rate determination step, char reactivity and burnout behavior need detailed discussion which has been elaborated in the next section.

2.1.3. Reactivity of char and burnout behavior

The fraction of combustible matter present in the parent fuel that is converted to gaseous products, with the remaining part left as carbonaceous residue is known as degree of carbon burnout. In pulverized fuel combustion, the carbon burnout influences the thermal efficiency of the plant and quality of fly ash [57]. The burnout in pulverized fuel combustion is dependent on the char reactivity of the fuel particles. The reactivity of char particles was found to be influenced by various factors such as fuel characteristics, heating rate, temperature and pressure [41,57]. Char reactivity of different solid fuels is compared through TGA studies, and one of such studies reported experimental results at kinetic controlled condition [58]. The reactivities of different solid fuels vary almost four orders of magnitude under identical conditions. In case of coal chars, the char reactivity generally decreases with increasing carbon content of the coals, which is consistent with the tendency observed in another study [57]. Studies also revealed that the reactivity of biomass chars is generally greater than that of coal chars [59,60]. The residence time, the shape and the ignition characteristics of fuel particles influence the carbon burnout in co-combustion of coal and biomass. The investigations on the influence of co-combustion on the burnout were carried out by different researchers with a number of different coals and biomass [61–63]. Co-combustion of coal and biomass may either increase or decrease the burnout, compared to dedicated coal combustion, depending on the fuel characteristics and combustion environment.

The beneficial effect of biomass addition on the burnout was also observed in the investigations on (i) co-combustion of lignite and sawdust in an isothermal flow reactor [61], (ii) co-combustion of coal and a number of different biomasses in a down fired combustor [64], and (iii) co-combustion of different coal and biomasses both under air and oxy-fuel combustion conditions [65]. Normally, the observed effect is a complex combination of several factors. The reactivity of biomass char was usually greater than that of coal char due to the catalytic effect of inorganic elements and the porous structure [58–60].

In addition, the biomass char particles are nonspherical and having large aspect ratios, which favor heat transfer and residence time, compared to the corresponding spherical particles [66]. The possible higher flame temperature during co-combustion of coal and biomass may also be an advantage for the burnout [54,55]. Some studies reflected that the addition of biomass can reduce burnout during co-combustion. Experiments in a pulverized fuel combustion test facility shows that co-combustion of coal and biomass may result in a decreased burnout compared to pure coal combustion. This decreased burnout may be due to the large biomass particle size used in the experiments and the relatively short residence time in the test facility [16]. Reactivity of biomass char greater than that of coal sample was observed. Selection of biomass with suitable particle size and moisture content was reported to be very important and control of these parameters was found to be essential to obtain a satisfactory burnout in

co-combustion of coal and biomass [10,16]. Work carried out by different groups of researchers in the area of GHG emission during co-combustion have been illustrated in the next section.

2.2. Environmental aspects of biomass co-combustion: GHG emission

In general, biomass is considered to be CO₂-neutral fuel [67], meaning that combustion of biomass should not increase the CO₂ level in the atmosphere, because the amount of CO₂ emitted during conversion process equals CO₂ which was assimilated into the plants during the process of their growth (where both processes took place within relatively small period of time). However, the concept of biomass being a neutral fuel is only true, if we do not include the emissions related to biomass harvesting, transportation, pre-treatment etc., and when the total carbon sequestered in the atmosphere remains constant (the cycle of growth and harvest is maintained). In order to properly estimate the environmental consequences of co-firing, life cycle analyses should be applied, to make sure that not only the energy conversion-related impacts are included, but also other potential environmental burdens along the whole life cycle of biomass are considered. The Life Cycle Assessment studies show in general, that the use of biomass for electricity generation results in environmental benefits in comparison with coal-based systems [68–74]. These environmental profits include reduction in CO₂ emissions. Co-firing of biomass with coal reduces the emissions of greenhouse gasses (GHG) and traditional pollutants (SO₂, NO_x). SO_x emissions almost always decrease due to co-firing of biomass with coal, often proportionally to biomass thermal load, as most biomasses contain less sulfur than coal. NO_x emissions can increase, decrease or remain the same when co-firing biomass with coal [11,75] and the effect varies with biomass type, firing and operating conditions [75]. For example wood contains relatively little nitrogen and therefore co-firing of coal with wood tends to decrease the total NO_x emissions [75]. Assuming the above is correct for all bio-systems, utilization of biomass instead of coal, whether in stand-alone or co-firing option, should always bring environmental benefits. For example, if the environmental impact of storage is omitted in one study, and the other study assumes emissions of N₂O from stored biomass as estimated in [76], the impact on the final result with regard to GHG emissions could vary significantly. In this case even small amounts of N₂O emitted during storage of biomass could lead to 310 times higher impact expressed in CO₂eq (Global Warming Potential of N₂O is equal to 310). There may be various constraints associated with biomass co-firing such as fuel preparation, handling, feeding, unstable combustion, deposit formation, corrosion, erosion, ash deposition and fly ash utilization [10,75–77]. Addressing these challenges could result in certain environmental impacts (e.g. if due to corrosion, certain elements of the system need to be replaced, the impact related to disposal of the worn-out element as well as the impact of production of new element should be accounted for the impact assessment). Waste products include wood waste material (e.g. sawdust, wood chips, etc.), crop residues (e.g. corn husks, wheat chaff, etc.), and municipal, animal and industrial wastes (e.g. sewage sludge, manure, etc.). Dedicated energy crops, including short-rotation woody crops like hard wood trees and herbaceous crops like switch grass, are agricultural crops that are solely grown for use as biomass fuels. These crops have very fast growth rates and can therefore be used as a regular supply of fuel. Co-firing of biomass residues, rather than crops grown for energy, brings additional greenhouse gas mitigation by avoiding CH₄ release from the otherwise landfilled biomass. It is believed that CH₄ is 21 times more potent than CO₂ in terms of global warming impact [16,78]. In addition, most of the fuel nitrogen in biomass is converted to NH radicals (mainly ammonia, NH₃) during combustion. Ammonia reduces NO to molecular nitrogen. Hence, lowering of NO_x emission level was also reported in co-firing of biomass [16,78]. Stored biomass wastes anaerobically (i.e. in the

presence of bacteria and moisture) release CH_4 , NH_3 , H_2S , amides, volatile organic acids, mercaptans, esters and other chemicals. By combusting the biomass, ambient emissions of these pollutants are reduced [78].

Liu et al. [79] studied the influences of co-combustion of coal and biomass on N_2O emission in a bench-scale fluidized bed reactor system. They found that co-combustion of biomass and coal can reduce the emissions of N_2O and NO_x . The emission of N_2O and NO_x was found to decrease with increase of the ratio of biomass to coal. The mechanism explanation of the reduction of the emissions of N_2O and NO_x by co-combustion of biomass and coal was reported to be due to quick release of volatile in biomass in the lower part of the fluidized bed, which produces a lot of radicals causing consumption of local oxygen and de-oxidation of N_2O and NO_x . Pedersen et al. [80] studied the effect of co-firing of straw and pulverized coal in a 2.5 MWt pilot-scale burner and a 250 MWe utility boiler. They experienced that an increased fraction of straw in the fuel blend resulted in a reduction of NO and SO_2 emissions. The lower SO_2 emission was partly due to a lower sulfur content of the straw and partly due to retention of sulfur in the ash, probably present as solid alkali sulfates. The reduction of NO emissions was due to lower conversion of the fuel-bound nitrogen. Increasing the straw fraction resulted in a larger release of volatiles including NO precursors, leading to conditions that can suppress formation of NO from fuel nitrogen. Spliethoff et al. [16] on the other hand investigated the effect of co-combustion of biomass on emissions in pulverized fuel furnaces. The investigations revealed the positive effect of biomass addition on emissions. Since biomass in most cases was found to contain considerably less sulfur than coal, an increasing biomass share in the thermal output made the SO_2 emissions to decrease proportionally. For sewage sludge, the emissions of SO_2 correlate with the sulfur content of the fuel. Rise in SO_2 emission was observed with an increasing share of this biomass. In all the cases ash formation was considered to be of serious concern. An evaluation of the CO_2 balance shows that, compared with the combustion of hard coal, the CO_2 emissions can be reduced by approximately 93%.

Kazagic et al. [81] recorded significant reductions for both NO_x and SO_2 emission as the process temperature was decreased. For both of the coal–biomass blends tested, there was a reduction of NO_x of 50% as the process temperature was reduced from 1400 °C to 960 °C. At the same time, no clear relationship was detected between NO_x emissions for the different coal–biomass blends. On the other hand, less SO_2 was measured for coal–biomass combustion compared to brown coal alone; at 1140 °C, there was 15% less SO_2 for the blend than the Kakanj coal alone, while it was 28% less for another blend.

Effects of co-combustion on plant operation were investigated by several researchers [2,9,52,82–87]. The positive effects are that SO_x and NO_x emissions usually decrease due to the lower sulfur and nitrogen content in biomass than in coal. Furthermore, alkali components in biomass ash can have an effect of SO_x removal. Since biomass has a high volatile content, it can also be used as reburn fuel for NO_x reduction from the coal combustion, which gives a further potential for significant decrease of the NO_x emissions. Besides NO and NO_2 , N_2O also was reported to be reduced significantly by co-firing of biomass in coal-fired fluidized bed boilers. Results of some applications [2,85,86] reflected that co-firing of biomass with coal have accomplished the following: (1) increased boiler efficiency, (2) reduced fuel costs and (3) reduced emissions of NO_x and fossil CO_2 . As biomass is a regenerable bio-fuel, reduction in net CO_2 emission through replacement of fossil fuel by biomass appeared to be quite evident [2,85]. Overall it was clearly vivid that co-firing of biomass with coal reduces CO_2 , SO_x and NO_x emission. In this regard ash formation and its deposition should also be understood properly for proper utilization of biomass.

2.3. Ash formation and deposition

In biomass ash-forming elements are present as salts, bound in the carbon structure (inherent ash) or they are attendant as mineral particles from dirt and clay introduced into the biomass fuel during harvest or transport (entrained ash). The compounds in inherent ash are homogeneously dispersed in the fuel and are much more mobile than the compounds in entrained ash and therefore are readily volatile and available for reactions in burning char [88].

A fraction of the ash-forming compounds in the fuel is volatilized and released to the gas phase during combustion. The volatilized fraction depends on the fuel characteristics, the gas atmosphere and the combustion technology in use. For example high combustion temperature and a reducing atmosphere have been reported to enhance the volatilization of the environmentally relevant heavy metals Zn, Pb and Cd [89].

In the reducing conditions and the high temperatures inside and on the surface of burning char even a small fraction present as refractory oxides, such as SiO_2 , CaO and MgO may be converted to more volatile SiO_2 , Ca and Mg and get volatilized. When released from the char as vapors these elements form very small primary particles in the boundary layer of the burning char particles due to re-oxidation and subsequent nucleation [90,91]. Primary particles formed by vaporization and subsequent nucleation in the boundary layer are very small in size, about 5–10 nm, but on their way in the flue gas they grow by coagulation, agglomeration and condensation [90]. These particles form the basis for the fine mode of the fly ash, characterized by a particle size < 1 μm . In contrast to the fine-mode fly ash particles from volatilized ash compounds, coarse fly-ash particles are larger, typically exceeds 5 μm [92,93].

Upon cooling of the flue gas in the convective heat exchanger section, vapors of volatilized compounds condense or react on the surface of pre-existing ash particles in the flue gas. Due to the much larger specific surface of the fine-mode particles compared to the coarse fly-ash particles the concentrations of condensing or reacting ash-forming elements increase with decreasing particle size. This explains some of the very high heavy-metal concentrations found in aerosol particles from combustion plants [89,92].

If the concentration of inorganic vapors in the flue gas and the cooling rate in the heat exchanger are both high, super saturation of these vaporous compounds could occur, causing formation of new particles by nucleation. In biomass combustion the most abundant volatile element is potassium originating from inherent ash (K in entrained ash is typically present as thermally very stable mineral silicate compounds and will not vaporize). However, according to gas phase kinetic considerations, the formation of K_2SO_4 was not always found to follow equilibrium and only a part of potassium in the gas phase was found to be converted [94]. According to the researchers in this area, the part of the gaseous potassium that does not form sulfates will either nucleate as KCl or K_2CO_3 or condensate on pre-existing particles at significantly lower temperatures than K_2SO_4 . The sulfation of KCl releases corrosive Cl which can catalytically react with the heat exchanger surface by the 'active oxidation' mechanism [95]. Grammel et al. investigated the alterations of ash quality and utilization aspects when co-firing coal with biomass. Co-combustion tests were performed in lab and semi-industrial scale facilities, using several coal–biomass blends. Results showed that properties of co-combustion residues are directly connected to the combustion conditions and the individual blend components. Biomass exploitation as secondary fuel in co-combustion processes sometimes said to be technically and economically feasible up to 20% w/w and the utilization of produced ash are possible without any major treatment [96].

Ash related issues such as slagging, fouling, corrosion and particulate emissions are of important concerns in co-combustion

of solid fuels. This is primarily because the secondary fuels applied in co-combustion, generally contain large amount of alkalis and chlorine that may be easily released to gas phase during combustion and create ash deposition. So, it is important to understand and address the ash related problems in co-combustion. In addition, the possible interactions among different solid fuels on ash related issues need to be evaluated thoroughly before the biomass–coal blends are recommended for co-combustion applications.

The influence of co-combustion on ash deposition in pulverized fuel combustion has been investigated through different scales of experiments [97–106]. These studies mainly focused on co-combustion of coal with different biomasses and other secondary fuels. Some of the secondary fuels with relatively low deposition rate, such as sawdust, were observed to be relatively safe, since co-firing coal with these secondary fuels would not significantly influence or even decrease the ash deposition rate [100,101]. According to a detailed investigation on co-firing peat and straw, the obtained ash deposition rate in co-firing is almost the same as that of pure peat combustion, when the mass share of straw is below 70 wt%. However, when the mass share of straw is between 70 wt% and 100 wt%, a significant increase of the ash deposition rate was observed [102–104].

Fouling of combustor surfaces is a major issue that has played an important role in the design and operation of combustion equipment. The main contributions to fouling come from the inorganic material in the fuel. The behavior of these inorganics is less well understood than that of organic materials. Because biomass fuels contain a larger variety of inorganic materials compared to coal; issues of fouling, corrosion and pollutant emissions need to be explored. This is particularly true for some agricultural residues and new tree growth where ash can have relatively high alkaline metal contents, particularly sodium and potassium [107]. Sodium and potassium lower the melting point of ash and, hence can increase ash deposition and fouling of boiler tubes. Baxter [97] addressed ash deposition and corrosion problems during coal and biomass combustion. He developed a mechanistic model to describe ash deposition in solid fuel combustors and postulated characteristics of ash deposits in biomass combustion. The major mechanisms of ash deposition were related to the types of inorganic material in the fuel blend and the combustion conditions. Ash deposition properties such as tenacity, emissivity, thermal conductivity and morphology were discussed in relation to fuel characteristics and operating conditions. The theoretical predictions were validated by experiments carried out with a variety of coal types. Baxter [97] concluded that the ash deposition rate in biomass combustion would peak at early times and then decrease monotonically. Savolainen [82] studied the slagging behavior of the boiler monitoring it visually and measuring from the process data (soot-blowing frequency, attemperation of water flows, etc.). During the co-firing tests, the boiler slagging and fouling were found to be at normal levels.

Pronobis [108] on the other hand studied the influence of biomass co-combustion on the fouling of boiler convection surfaces. In order to show the influence of co-firing biomass with bituminous coal on boiler efficiency, the calculations of the pulverized fuel (PF) OP 140 steam generator have been carried out. Typical Upper Silesian coal with medium fouling inclination was chosen as a basic fuel. Three kinds of biomasses have been taken into consideration: straw, wood and dried sewage sludge. The results confirmed that the properties of additional fuels cause deterioration of the boiler efficiency as well as the changes in boilers operational parameters (amount of water injected in attemperators, ash stream, hot air temperature). Pronobis [109] also studied the influence of biomass co-combustion on boiler furnace slagging by means of fusibility correlations. In order to show the influence of co-firing biomass with bituminous coal on

ash properties, calculations of fusibility correlations have been carried out. Two Upper Silesian coals (with lower-LS and higher-HS slagging inclination) were chosen for emphasizing the influence of basic fuel. Four kinds of biomasses were considered: straw, wood, dried sewage sludge and bone meal. The general conclusion is that co-firing biomass increases the fireside slagging hazard and the most difficult additional fuels are sludge and bone meal. Abreu et al. [101] investigated on ash deposition during the co-firing of bituminous coal with pine sawdust and olive stones in a laboratory furnace. The main objective of this study was to relate the ash deposit rates with the type of biomass burned and its thermal percentage in the blend. The thermal percentage of biomass in the blend was varied between 10% and 50% for both sawdust and olive stones. For comparison purposes, tests have also been performed using only coal or only biomass. During the tests, deposits were collected with the aid of an air-cooled deposition probe placed far from the flame region, where the mean gas temperature was around 640 °C. A number of deposit samples were subsequently analyzed on a scanning electron microscope equipped with an energy dispersive X-ray detector. Results indicated that blending sawdust with coal decreases the deposition rate as compared with the firing of unblended coal due to both the sawdust low ash content and its low alkalis content. The co-firing of coal and sawdust yielded deposits with high levels of silicon and aluminum which indicated the presence of ashes with high fusion temperature and, thus, with less capacity to adhere to the surfaces. In contrast, in the co-firing of coal with olive stones the deposition rate increases as compared with the firing of unblended coal and the deposits produced present high levels of potassium, which tend to increase their stickiness. Xu et al. [110] studied the effect of co-firing straw with two coals on the ash deposition behavior in a down-fired pulverized coal combustor. This investigation examined the variation of ash deposit when co-firing wheat straw with both high kaolinite, low-sulfur YanKuang (YK) coal and low-kaolinite, high-sulfur WenNan (WN) coal at different ratios. The experiments were carried out in a 25 kW lab-scale one-dimensional down-fired combustor, in which a temperature-controlled deposition probe was developed to collect deposit samples for further mass, morphology, or chemical analyses. A significant increase in ash collection efficiency was observed in the cases of co-firing straw with WN but became insignificant when co-firing straw with YK. The formation of low-melting alkali–aluminum silicates instead of the sulfation of alkali chloride plays an important role in explaining the changing of two typical deposition mechanisms during ash deposition. Finally, the vital role of fine particles as the adhesive or glue between coarse ash residues was verified by scanning electron microscopy pictures.

Heinzel et al. [105] also studied slagging behavior in co-combustion of coal and biomass. The co-combustion experiments in the pilot scale test facility revealed that the co-combustion tests with a 25% share of biomass, resulted without causing slagging and fouling problems. In contrast to the experiments with 25% of biomass, a sintered layer covering the probe was observed when firing with 50% share of straw and similar slag layer was also found on the cooled metal probe when firing pure straw.

Kazagic et al. [81] studied ash deposition behavior of different Bosnian coal types and biomasses fired in an electrically heated entrained pulverized fuel flow experimental reactor. They observed that in the co-firing test trials, there was no significant difference recorded in the ash deposition characteristics of the coal–biomass ash samples against the single coal ash samples at temperature up to 1250 °C. Above this temperature, fouling was significant for the coal–biomass blends. Teixeira et al. [111] evaluated slagging and fouling tendency during biomass co-firing with coal in a fluidized bed combustor. They concluded that the woody biomass can be successfully used as bio-fuel without

significant slagging and fouling problems. Generally it was concluded that though co-firing of biomass increases the fireside slagging hazard, experiments indicate certain percentage of biomass can be utilized without slagging and fouling problems. However for better understanding burning characteristics of these types of blends require special attention.

2.4. Burning performances of coal–biomass blends

There are several reasons to blend biomass with coal or with other types of fuel prior to burning. Sometimes bio-fuel products are mixed with coal to achieve better control of the burning process. In co-combustion processes, a volatile matter content greater than 35% is sought in order to provide a stable flame, which could be attained by using biomass [48,112]. Furthermore, existing coal-fired power plants may continue to be used with very few modifications, and as a final argument, the co-utilization of biomass or waste in existing coal-fired plants is likely to result in a number of environmental, technical and economical benefits [48].

Several researchers [6,113–124] investigated co-combustion behavior of coal/biomass blends in different scales to evaluate resultant combustion characteristics, heat release pattern, kinetics etc. Basic co-combustion studies were carried out mainly with the help of a Thermogravimetric Analyzer (TGA); bench scale studies were carried out with the help of furnaces like the drop tube furnace, the fixed bed combustor etc. Pilot scale combustion test facilities were also utilized for co-combustion studies for possible application of co-firing in an actual boiler.

Thermogravimetric analysis (TGA) is one of the most common techniques used to rapidly investigate and compare thermal events and kinetics during the combustion and pyrolysis of solid raw materials, such as coal and woods [112,125–128], paper sludge [124], rice husks [129–133], woody shells of hazelnut [134,135], olive milling residue [130], wheat straw [112], pine sawdust [43,136]. TGA is able to measure the mass loss of a sample as a function of time and temperature. The temperatures, at which combustion or decomposition reactions in the sample start, can also be followed by TGA. Moreover, quantitative methods can be applied to TGA curves in order to obtain kinetic parameters. The kinetics of the thermal events was determined by several researchers by applying the Arrhenius equation to the separate slopes of constant mass loss [112,137–139]. The information obtained from TGA combustion profiles can be used for an initial evaluation of the combustion performance at industrial scale. TGA techniques operate at different conditions and the experimental protocol is set in accordance with the environment prevailing in the combustor. Other bench equipments such as drop tube furnaces and entrained flow reactors simulate more closely the combustion conditions of industrial pf combustors. Ranges of informations which can be derived from thermoanalytical studies (basically TGA, DSC, DTA etc.) are really very useful from a fundamental viewpoint, and for comparison amongst the samples [140,141]. A knowledge of the combustion characteristics and combustion kinetics is essential for understanding and modeling combustion in furnaces at industrial scale, both in the case of 'co-firing of biomass with coal' and 'firing of biomass alone' [142]. Such knowledge is also necessary for the design and operation of combustion systems [143]. According to Shen et al. [138], a good understanding of the decomposition of biomass during thermochemical conversion is important for developing an efficient processing technology. Most studies related to the kinetics of biomass decomposition are focused on pyrolyzing these materials under inert atmospheres. However, the most recent research has been directed towards the study of biomass decomposition in oxidative environments [138,144,145] a subject about which information is still scarce. A study on co-combustion behavior of

paper sludge with low rank coal [124] reflected improvement of the combustion behavior of the blends, although blending of 10% paper sludge with coal did not affect the devolatilization or combustion reactivities of the individual fuels. Furthermore, the composition and the fusibility of the ashes varied in proportion to the paper sludge content in the mixture, fluid temperatures being high for both materials. It was also found in this study [124] that blending of paper sludge with coal, somehow improved the slagging/fouling potential of the sub-bituminous coal. Combustion behavior of blends of rice husks and pulverized coal [129] in TGA showed that a three-stage reaction and the correlation between the char yield and the biomass blending ratio was strongly characterized by a linear relationship. Analysis of the observations revealed that the synergistic effects between coal and biomass were absent or that the fuels had no interaction. The effect of co-combustion on the burnout of lignite/biomass (woody shells of hazelnut) blends was also studied in TGA [134]. The results were interpreted considering lignite properties and the major biomass ingredients such as cellulose, hemi-cellulose, and lignin. Results showed that burnouts obtained for the blend samples were not always the values which are calculated from the fractions of the experimental values of the parent samples. The addition of hazelnut shell up to 8 wt% into lignite, provided higher burnouts than the expected theoretical ones. However, the addition of 10 wt% biomass played a reducing role on the burnouts. On overall basis, burnout characteristics of the blends up to 10 wt% during co-combustion was concluded to show a synergistic effect, whereas additive effects were found to be more favorable in the case of the blend having a biomass content of 20 wt% and apparent activation energy; maximum burning rate was found to follow the additive behavior for the blend samples. In a particular study with Indian and Indonesian coal [123], co-combustion behavior of coal and municipal solid waste (MSW) in TGA was reported. The ignition temperature of the coal/MSW blends showed a strong dependence on the amount of energy released by volatile combustion. Further, the blending of the treated MSW was reported to improve the combustion characteristics of high ash Indian coal, indicating the combination of Indian coal and the treated MSW is feasible for co-firing application [123]. Wang et al. [112] observed that when coal is added to biomass, the volatilization rate is modified, the heat released is affected and the combustion residue is reduced under the same final combustion temperature leading to increase in the combustion efficiency. In another study [133] the high VM content of the biomass fuels (rice husk and bamboo) was reported to play a key role to shorten the combustion time scale of co-combustion as compared to coal combustion. Apart from the reduction of combustion time, particle and polyaromatic hydrocarbon (PAH) emissions improvements were also observed in this co-combustion study. Co-combustion characteristics of low rank coal and rice husk (both raw and char) were investigated by Zakaria et al. [131]. In this study double DTG evolution profiles were observed in the case of raw biomass coal blending. But in the case of biomass char blending single DTG evolution profile was observed. This indicated more synchronization of combustion profiles of both the components during co-firing of biomass and coal as compared to combination of raw biomass and coal. Thermal behavior and kinetics of coal/biomass blends during co-combustion were also studied by Gil et al. [136]. They observed no significant interactions between coal and biomass, since no deviations were noticed from the expected behavior, in these experiments. However, the results showed that the chemical first order reaction is the most effective mechanism for the first step of biomass oxidation and for coal combustion. In order to find out whether interactions between the components of the blends occurred, the theoretical DTG curves of the blends were calculated as the sum of the decomposition curves of each individual

component in their study [136]. Several authors, have observed interactions between the components of coal/biomass blends [128,137], while some others have reported the additive behavior of different combustion parameters of coal–biomass blends [48,49,146–148]. Fitzpatrick et al. [149] studied the co-combustion of coal and pine wood in a fixed bed combustor and they observed synergy in organics emissions from the coal/pine wood blends, with lower emissions than would be expected on an additive basis. Some other researchers [112,123,134,135,150–153] also observed a synergistic effect during coal and biomass co-combustion. However, other group of researchers did not observe the synergistic effect performed in various analytical instruments (basically TGA) and in bench scale setup during co-combustion of some specific combination of coal and biomass [129–131,136,154,155]. Both the groups of researchers specified experimental conditions for co-combustion studies in their publications referred above.

Activation energy and pre-exponential factors of the individual component and blends were evaluated by several researchers [123,136,142,146,151,154,156]. Each of these studies reflected the difficulty of reaction to occur and intensity of thermal chemistry for a set of fuels (blends and its components fuels), under the identical combustion conditions of terminal temperature and heat-up rate. In some study activation energy and pre-exponential factor were found to decrease with the increasing level of biomass content in coal [112,123]. Such trends indicated a positive effect of biomass blending during co-combustion. This is because, relatively weak chemical bonds of biomass are less resistant to heat compared with coal having more complex bonds due to its much more maturity.

Drop tube furnace study and fixed bed combustor study were conducted by several researchers [55,56,129,133,157] to study co-combustion behavior of coal–biomass blends. Ignition behaviors of coal–biomass blends in a drop tube furnace were found to have similar characteristics as coal of higher volatile matter in the blend and depend on its proportion in the blend [56]. The results from their study are used to predict the operation of a coal fired power plant in terms of fuel selection, fuel blending, and flame stability [56]. It has been reflected in a study [55] that addition of biomass into low-rank coal affects the combustion behavior, especially for ignition enhancement due to high volatile matter present in biomass. Synergistic effects were detected in the co-firing tests with sawdust in combination with brown coal and lignite. Trial with coal/biomass mixtures at 93:7 and 80:20 wt proportions were performed by firing in a 20 kW pulverized fuel (PF) entrained flow reactor in their study [157].

Negative effects of co-firing were also reported to be additional investment cost for biomass pretreatment, several issues like boiler retrofitting, higher operation cost due to increased fouling and corrosion, and a possible decrease of the efficiency of electric power generation. Besides potential poisoning of selective catalytic reduction (SCR) catalyst the efficiency of electrostatic precipitators may also be reduced [11]. Furthermore, the utilization of the ash and the residues from the flue gas cleaning system was proposed to be considered for possible implementation of co-firing of coal with biomass [9]. Moreover, possibility of increase in the unburnt carbon content was also indicated in the case of co-combustion of coal and biomass. Usually a biomass input in the range of 5–10% was found to be acceptable without major influence on the residues and from energy input point of view also the said range of biomass content was generally found to be acceptable [2,85,86]. A very limited number of studies were available in literature in co-combustion of coal and biomass chars [131,135,151,158,159]. The combustion behavior of the blends of coal and biomass chars was greatly influenced by the rank of each coal (hard coal or lignite) and the proportion of each component in

the blend. Combustion performance of the blends showed some deviation from the expected weighted average of the constituent chars [158]. It was found that addition of biomass char led to important variations in some thermal properties which could not be explained by the additive behavior. However it can be concluded in general that the combinations of synergistic interactions and additive behavior govern the thermal properties of the coal–biomass char blends during co-combustion [135]. It has been reported by Kastanaki et al. [158] that biomass chars obtained after partial devolatilization is more reactive than those obtained from coals. Biomass chars were found to have porous and highly disordered carbon structure and belong to the class of most reactive carbon materials. The porosity within the chars causes more accessibility of the reactive gas to active sites resulting in the very good combustion reactivity [160]. The elevated energy density and decreased ash content of the biomass char improved its combustion behavior when co-fired with coal/lignite for energy production [151]. Moreover, biomass char-coal co-combustion is a new concept as has been reflected in published papers [131,135,151,158,159]. The use of biomass char instead of raw biomass may extract several advantages. Followed by the above work, some recent publications [154,161–166] on this subject also revealed the potential application of biomass char as co-fuel. Finally, it may be concluded that in co-combustion both additive and synergistic effects were observed in most of the co-combustion studies discussed here.

3. Conclusion

Global concerns on the effect of GHG emissions from combustion of fossil fuels have prompted initiatives in search of alternate pathways for reducing the emissions from coal fired power plants. Numerous investigations on the suitability of biomass, a carbon neutral substance, as a blend component in coal fired boilers indicate co-combustion of coal with biomass is one promising option for cost and emission reductions in coal fired boilers. Notwithstanding the uncertainties associated with the use of biomass as co-fuel with coal in terms of devolatilization, burning and ash depositional characteristics, the advantages of using biomass greatly outweigh the constraints associated with it. Utilization of the large quantity of various types of biomasses being available in different locations as co-fuel would however, require a long drawn strategy based on a strong policy framework. Other than the technical constraints, ensuring the sustained availability, regeneration of biomass, transportation and preparation need to be addressed to make this potential option an economically and technologically viable one.

Moreover, it may be concluded that using biomass in boilers offers many advantages like mitigation of hazardous emissions like CO₂, NO_x, SO_x, CO, increased combustion efficiency, wide flame length, flame temperature etc. Biomass is different from coal in many important ways, including the organic, inorganic and energy content and physical properties. These differences may affect replacing coal by biomass and also affect co-firing of biomass and coal boilers. Thus, further studies are very much needed to be conducted such as improvement in boilers design, materials and combustion technology.

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